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RESEARCH PAPER

Charnockite microstructures: From magmatic to metamorphic

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Abstract Charnockites sensu lato (charnockite-enderbite series) are lower crustal felsic rocks typically characterised by the presence of anhydrous minerals including orthopyroxene and garnet. They either represent dry (H_2O-poor) felsic magmas that are emplaced in the lower crust or granitic intrusions that have been dehydrated during a subsequent granulite facies metamorphic event. In the first case, post-magmatic high-temperature recrystallisation may result in widespread metamorphic granulite microstructures, superimposed or replacing the magmatic microstructures. Despite recrystallisation, magmatic remnants may still be found, notably in the form of melt-related microstructures such as melt inclusions. For both magmatic charnockites and dehydrated granites, subsequent fluid-mineral interaction at intergrain boundaries during retrogradation are documented by microstructures including K-feldspar microveins and myrmekites. They indicate that a large quantity of low-H_2O activity salt-rich brines, were present (together with CO_2 under immiscible conditions) in the lower crust.

1. Introduction

At the end of the 19th century, Sir Thomas Holland, the head of the Geological Survey of India, suggested the name of "charnockite" for a massive, equigranular dark-greenish rock forming the Saint-Thomas Mount, a small hill located at Pallavaram, a suburb of Chennai (formerly Madras) in the Tamil Nadu State. Most authors refer to the paper published in 1900, but according to an article published in The Hindu (national newspaper in India) on 27 May 2002, the name was already given earlier in an address entitled "The petrology of Job Charnock's tombstone", which was delivered to the Asiatic Society of Bengal in 1893: "As this is a new type of rock… I would suggest for it the name of Charnockite, in honour of the founder of Calcutta, who was the

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unconscious means of bringing, perhaps, the first specimen of this interesting rock to our capital."

Holland's definition of charnockites was refined in a subsequent paper published eight years later (Holland, 1908), in which it was given as "a quartz-feldspar-hypersthene-iron minerals-bearing rock", of a blue-grey to greenish colour (later referred to in the French literature as "couleur malgachitique", e.g. Lacroix, 1922). Holland was convinced that the charnockites in southern India were magmatic in origin. Further, he also recognised that at the type locality charnockite occurred together with a series of other contemporaneous rock types, ranging from acid (charnockites) to basic (norites or ultrabasic pyroxenites). The fact that the charnockites in southern India have later been reinterpreted to be metamorphic rocks (Cooray, 1969) has resulted in a more general redefinition of charnockites by Pichamuthu (1969) as being a quartzo-feldspathic rock with orthopyroxene. Since then, charnockites have been described in the literature, amongst others, as orthopyroxene-bearing lower crustal rocks that occur mostly in granulite facies terrains as igneous plutons, gneisses, charnockitised amphibolitic gneisses (i.e., incipient charnockites), pegmatites, and migmatites (Newton, 1992). Considering the variety of these descriptions, it is no surprise that there is some confusion about charnockites (e.g., Newton, 1992; Frost and Frost, 2008). In context with the occurrences mentioned by Newton (1992), charnockites can essentially be considered to be either igneous (crystallisation product of an anhydrous melt) or metamorphic (granite dehydration during granulite facies metamorphism) in origin.

The topic of this paper is to review and introduce some new aspects of the study of microstructures in igneous and metamorphic charnockites. Fortunately, substantial advances have recently been made in this too often disregarded field (e.g., Vernon, 2004; Holness et al., 2011). This study may serve as a guide to petrographically distinguish igneous from metamorphic charnockites and establish a mineral chronology, which is indispensable for geochronological studies and in particular fluid inclusion studies. Fluid inclusions are sometimes extraordinarily abundant in charnockites and of critical importance for understanding the formation of these rocks.

For the purpose of this paper, we would like to comment on the charnockite definition introduced by Frost and Frost (2008). Frost and Frost (2008) define charnockites as (p. 41): "…an orthopyroxene (or fayalite)-bearing granitic rock that is clearly of igneous origin or that is present as an orthogneiss within a granulite terrane." Our first remark on this definition is that we would prefer to add garnet to orthopyroxene/fayalite, as garnet and orthopyroxene charnockite varieties are so narrowly connected in many regional occurrences (e.g., Ansignan charnockites, Agly Massif, French Pyrenees, Fig. 1). Note that, in general, garnet-bearing charnockites do not show the "malgachitic" colour, which only occurs in orthopyroxene-bearing garnet-absent varieties. Further, the second part of the definition by Frost and Frost (2008) indicates that gneissic charnockites (referred to as "orthogneiss", a name that we would like to change to "charnockitic augen gneisses") only occur in granulite terranes. This is not entirely true; for example, in southern Norway (i.e., the Bamble Province, e.g. Touret and Nijland, 2012), elongated bodies of charnockitic augen gneisses (i.e., Hovdefjell and Ubergsmoen augen gneisses) occur outside of the granulite domain, north of the regional amphibolite/granulite boundary. Conversely, many igneous charnockites that occur within granulite terrains have been subjected to a metamorphic granulite facies overprint, which can obliterate the original igneous structures. Finally, we would regret the elimination all other terms of the "charnockites" series (i.e., QAP classification as proposed by LeMaitre in 1989) as suggested by Frost and Frost (2008). Charnockite series are the lower crustal equivalents from the granite series in granulite facies terrains and the fact that these rocks are consistently ignored by the granite specialists (charnockite is not even mentioned in recent books on granites, e.g. Bouchez and Nédelec, 2011) does not circumvent the fact that they should be studied in parallel. We agree that terms including opdalite and jotunite are not frequently used and could easily be excluded, but a rock like mangerite is extremely important in the well known anorthosites-mangerites-charnockite-granite (AMCG) complexes (Emslie et al., 1994) and the "charno-enderbite" labelled as a "terminological monstrosity" by Frost and Frost (2008) is in our opinion as useful as and not much more complicated than "granodiorite".

1.1. Metamorphic vs. igneous charnockites

Initially, the idea that orthopyroxene could not crystallise directly from a granitic magma (Howie, 1955) was used as evidence that charnockites had to be granitic rocks dehydrated during

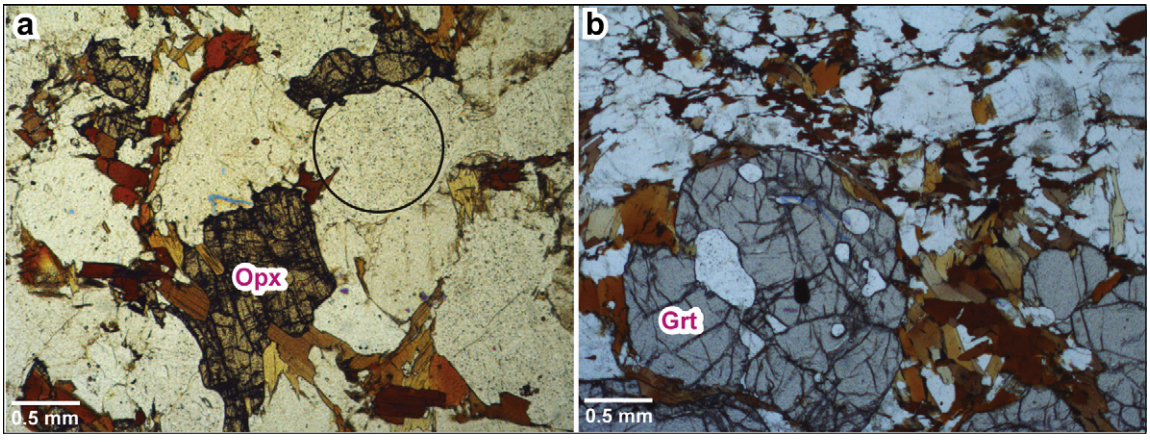

Figure 1 Microphotographs of two types of Ansignan charnockites (Agly Massif, French Pyrenees) in plane polarised light (thin sections courtesy M. Demange). a: orthopyroxene-bearing charnockite, b: garnet-bearing charnockite. The garnet-bearing variety is more deformed (charnockitic augen gneiss). In both cases biotite crystals are partly bent and tend to occur along feldspar intergrain boundaries. Feldspar in the orthopyroxene-bearing charnockite comprises CO_2 dominated fluid and empty inclusions (a). Quartz blebs in garnet comprise brine inclusions (not visible in the microphotograph).

metamorphism. More substantial evidence for this interpretation was derived from so called incipient charnockites, which recently has been extended to the scale of entire charnockite massifs (Santosh and Omori, 2008) such as the Nagercoil Massif in southern India (Rajesh et al., 2011). Here, orthopyroxene is formed as a result of solid-state dehydration reactions driven by a lowering of the H_2O-activity. The H_2O-activity can be lowered by either the infiltration of low-H_2O activity fluid (high-density CO_2 and/or salt-concentrated brines) (e.g., Hansen et al., 1984, 1987; Perchuk and Gerya, 1993; Harlov, 2012; Touret and Huizenga, 2012), traces of which being preserved in fluid inclusions, or by the removal of the fluid phase along fractures (Srikantappa et al., 1985).

Alternatively, charnockites can also represent dry granitic melts in which orthopyroxene has crystallised from the magma (e.g., Frost and Frost, 2008). Kramers and Ridley (1989) have demonstrated that charnockite-enderbite suites could directly crystallise from a sialic magma layer in Archean granulites. In most cases, emplacement of charnockitic magmas occurs in a lower crustal (granulite facies) environment in which the charnockitic magmas and the metamorphic host rock (in particular ultrahigh-temperature granulites) are in (near) thermal equilibrium. This process prohibits widespread contact metamorphism except in rare cases in which charnockites are emplaced in amphibolite-facies rocks causing high-temperature, low-pressure contact metamorphism. Examples of these include the anorthosite-mangerite-charnockite complex in Rogaland (Bingen et al., 2008) and the Hovdefjell intrusion in the Bamble Province (Nijland and Senior, 1991), both in southern Norway.

The general absence of a temperature difference between intruding charnockitic magmas and its surroundings in the lower crusts is the prime cause of the ambiguities between a magmatic and metamorphic origin of charnockites. Recrystallisation at granulite facies conditions may result in the (partial) overprinting of igneous microstructures if charnockites are emplaced in the lower crust (e.g., Frost and Frost, 2008). Such a scenario is valid for those cases in which the emplacement of the charnockitic magma and granulite metamorphism was almost contemporaneous (e.g., Frost and Frost, 2008). This is notably the case in southern Norway, where charnockites and enderbites are emplaced during successive metamorphic events, covering a range of about 200 Ma, i.e. between ~1130 Ma in the east (Bamble) to ~900 Ma in the west (Bingen et al., 2008). Another example is the Ansignan charnockite in the French Pyrenees (Fonteilles, 1970), which is emplaced at high-grade metamorphic conditions (Respaut and Lancelot, 1983; Olivier et al., 2004). The Ansignan charnockite intrusion is synchronous with Hercynian granulite metamorphism ("coeval events", p. 238 in Olivier et al., 2004) and slightly older than 300 Ma (Respaut and Lancelot, 1983). About 20 Ma after emplacement, local melting and assimilation of host gneisses has caused the formation of the garnet-bearing variety (leptynitic according to the French nomenclature).

2. Microstructures in igneous charnockites

Microstructures in igneous charnockites include the following: (i) magmatic mineral textures that have been preserved during subsequent recrystallisation, (ii) melt remnants, which are proof of the existence of a melt phase and thus magmatic origin of a rock (e.g., Thomas et al., 2006), and (iii) post-magmatic high-temperature metasomatic features, typically occurring along mineral intergrain boundaries.

2.1. Igneous mineral textures

Igneous microstructures in charnockites include a porphyritic texture (e.g., Ridley, 1992), characterised by euhedral to subhedral pyroxene and feldspar (e.g., Shelley, 1993; Frost et al., 2000), which may have a slight preferred orientation. However, anhedral feldspar is not uncommon in igneous rocks due to impingement (e.g., see Fig. 3.45 in Vernon, 2004). Feldspar may show Carlsbad twinning and compositional zoning in the case of plagioclase (Shelley, 1993). Charnockitic augen gneiss in southern Norway in which the augen represent K-feldspar phenocrysts (e.g., Vernon, 1990) (Fig. 2), are an example of charnockites showing such a porphyritic texture. Further igneous microstructures include myrmekitic intergrowths of biotite-quartz ± plagioclase parallel to the biotite cleavage next to orthopyroxene (Ridley, 1992). This texture can be evidence for the presence of a melt phase where biotite-quartz ± plagioclase were formed according to the reaction Opx + melt → Bt + Qtz (Kramers and Ridley, 1989; Bohlender et al., 1992; Ridley, 1992), or Opx + melt → Bt + Qtz + Pl (Sawyer, 1999). Ridley (1992) suggested these reactions as alternative to the metamorphic hydration reaction Opx + Kfs + H_2O → Bt + Qtz based on the observation that (1) biotite and quartz do not systematically occur along orthopyroxene-K-feldspar grain boundaries, and (2) biotite-quartz intergrowths are observed in absence of orthopyroxene/K-feldspar, indicating that orthopyroxene was completely consumed in the above mentioned reactions.

The accessory minerals apatite and zircon are sometimes assumed to indicate a magmatic origin, especially if they are euhedral or contain melt inclusions. However, they may occur in magmatic charnockites as well as in granites, which means that they can be of little use to distinguish between magmatic charnockites and dehydrated granites. It is possible though that, to some extent, zircon recrystallisation may have occurred in dehydrated granites. We are not aware of detailed investigations made in this field, which could be an interesting line of research for future studies.

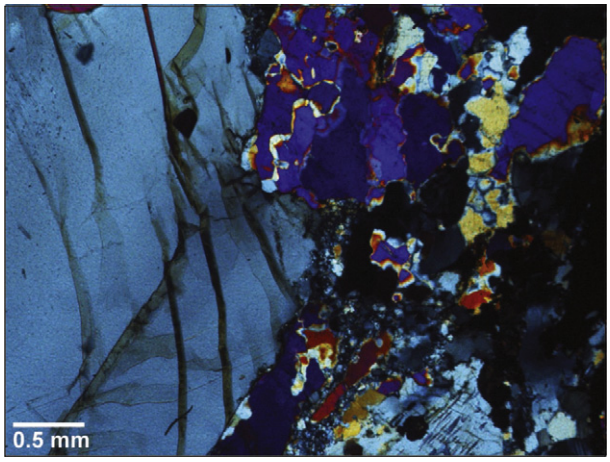

Figure 2 Microphotograph (crossed polarised light) of Hovdefjell charnockitic augen gneiss showing remnants of a large K-feldspar phenocryst (left part of the microphotograph) surrounded by a recrystallised matrix (bright colours, right part of the microphotograph). Fractures in the K-feldspar phenocryst are filled with beidellite giving the rock its dark appearance.

It must be emphasised that recrystallisation may destroy any original igneous microstructures, in particular when recrystallisation is associated with deformation (Ridley, 1992). Therefore, igneous microstructures in charnockites are rarely preserved unless the recrystallisation is minor or absent (see examples of igneous charnockite/enderbite described by e.g., Van den Kerkhof and Grantham, 1999; Frost et al., 2000; Percival and Mortensen, 2002).

2.2. Melt remnants

Melt remnants are a clear indication of the igneous origin of charnockites and can be in the form of melt (or melt derived) inclusions (e.g., Roedder, 1984) or typical melt-related microstructures (Sawyer, 1999; Holness and Sawyer, 2008; Holness et al., 2011).

2.2.1. Melt inclusions

Recrystallised melt inclusions in granite quartz were for the first time observed by Henry Clifton Sorby in 1858 (see Fig. 1 in Frezzotti, 2001), which was also the first time that the polarising microscope was used for petrographic studies. They have been the subject of constant research in the former Soviet Union (e.g., Sobolev and Kostyuk, 1975) whereas they have only recently been rediscovered in western studies (e.g., Touret and Frezzotti, 2003; Lowenstern, 2007). The fundamental technique that is used for studying melt inclusions, besides petrography, includes remelting at high temperature (e.g., Roedder, 1984; Frezzotti, 2001; Lowenstern, 2007), which can be used to estimate the crystallisation temperatures. Melt inclusions, however, may be affected by processes including degassing, oxidation, and re-equilibration with the host mineral (e.g., Roedder, 1984). These processes may occur during natural cooling and/or remelting experiments, resulting in an erroneous determination of crystallisation temperatures. For example, the disappearance of fluids by degassing may lead to very high remelting temperatures, sometimes even higher than the melting temperature of the host mineral. Despite these shortcomings, melt inclusions can supply a wealth of information on the nature and composition of the melt phase and associated fluid phase(s) if present in, for example, the lower crust.

Melt inclusions in lower crustal rocks are not likely to be preserved due to chemical re-equilibration and recrystallisation during (slow) cooling (Holness et al., 2011) unless cooling has been interrupted (e.g., granulite xenoliths that have been brought to the surface in magmas). For example, melt inclusions were found in granulite and eclogite xenoliths in alkaline basalts in eastern Pamir (Chupin et al., 1997, 2001) (Fig. 3). Here, the melt inclusions occur in garnet, orthopyroxene, and kyanite and comprise a glass phase and a CO_2 fluid phase. The melt inclusions homogenise at temperatures of $\sim$1000 °C at an external pressure of $>$12 kbar. The glass phase in the melt inclusion represents a peraluminous rhyodacitic Cl-enriched melt phase that was CO_2 saturated in the lower crust (Chupin et al., 2001) indicating the presence of a high-salinity aqueous and a CO_2-rich fluid. Another example of melt inclusions found in granulite xenoliths includes the ones described by Cesare et al. (2009, 2011). They identified extremely small glass − and (larger) so-called "nanogranite" inclusions (see Figs. 2 and 4 in Cesare et al., 2009 or Fig. 7 in Cesare et al., 2011) in peritectic garnet in xenolithic granulites and migmatites (Cesare et al., 2009, 2011).

The discovery of melt inclusions in granulite facies metamorphic rocks by Chupin et al. (1997, 2001) and Cesare et al.

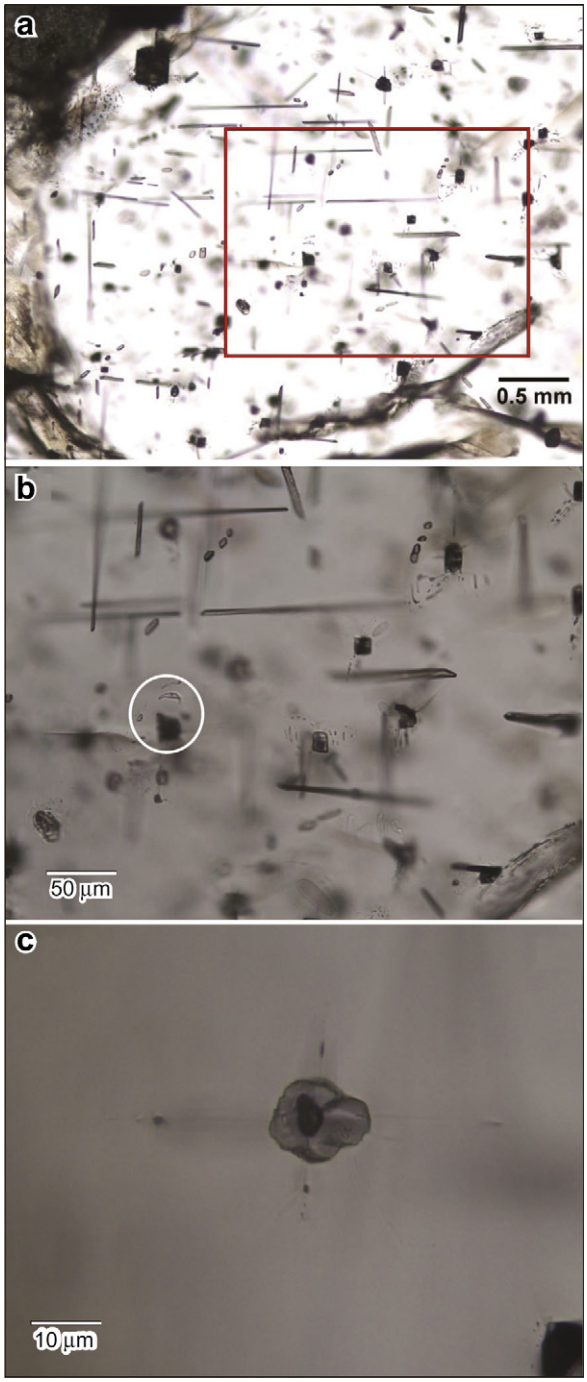

Figure 3 Melt inclusions in garnet in a granulite xenolith from Pamir (sample P5, courtesy V. Chupin) (Chupin et al., 1997) with increasing magnifications from (a) to (c). a: Aqueous fluid inclusions (presumably brines) around the melt inclusions represent fluids expelled from the melt. Inset: enlargement shown in (b). b: Detail of (a) (inset), showing a melt inclusion (out of focus) (white circle) surrounded by relatively small fluid inclusions that comprise aqueous fluids expelled from the melt. c: Detail of a melt inclusion (glass + CO_2 gas bubble) in sample P5. Temperature of homogenisation (disappearance of the gas bubble) is 1020 °C at 12 kbar external pressure (V. Chupin, personal communication).

(2009, 2011) is of great importance. It indicates that melt inclusions can be preserved in lower crustal rocks including igneous charnockites. To our knowledge, the only published study on melt inclusions in charnockites is from Bagiński et al. (2006), who described the occurrence of melt inclusions in plagioclase, orthopyroxene and quartz in charnockites from boreholes in NE Poland.

2.2.2. Melt-related microstructures

Traces of former melts may also be obtained from melt remnants in pore spaces at the intersection of three or more mineral grains (Holness et al., 2011). These remnants occur as a single mineral phase (e.g. plagioclase) with a droplet (curved) shape (Fig. 11 in Holness et al., 2011). A major difference with melt inclusions is that, in this case, the composition of the melt patch is mono-mineralic and not comparable to a melt composition. This can be explained by the fact that mineral phases did not simultaneously crystallise (cotectic crystallisation) due to nucleation problems, i.e. the mono-mineralic phases represent the final melt pockets after the other mineral phases have already been crystallised, which is referred to as sequential crystallisation by Holness et al. (2011). The shape has been preserved due to the lack of H_2O, prohibiting diffusion-related re-equilibration and straightening of the grain boundary (Holness et al., 2011).

Other possible evidence for melt remnants includes the occurrence of isolated, rounded zircons in antiperthite patches within plagioclase phenocrysts (Fig. 4) in igneous charnockites and in particular in enderbites. This texture is, in our experience, rather common although it has not been described in the literature before. The textural relationship between zircon and antiperthite patches is quite spectacular (Fig. 4) and the first impression might be that zircon may have served as a nucleus for feldspar exsolution. This interpretation, however, can be excluded as the position of zircon within antiperthite is variable and normally several zircon crystals (in most cases two, but sometimes up to four) are present in anthipertite. We, therefore, interpret these structures as former zircon-containing melt patches that are embedded in a growing plagioclase crystal. The mono-mineralic (K-feldspar) character of the melt remnant can be, as mentioned before, explained by sequential crystallisation (Holness et al., 2011). An alternative explanation might be that the original multi-phase assemblage has been subjected to post-magmatic fluid-induced alteration.

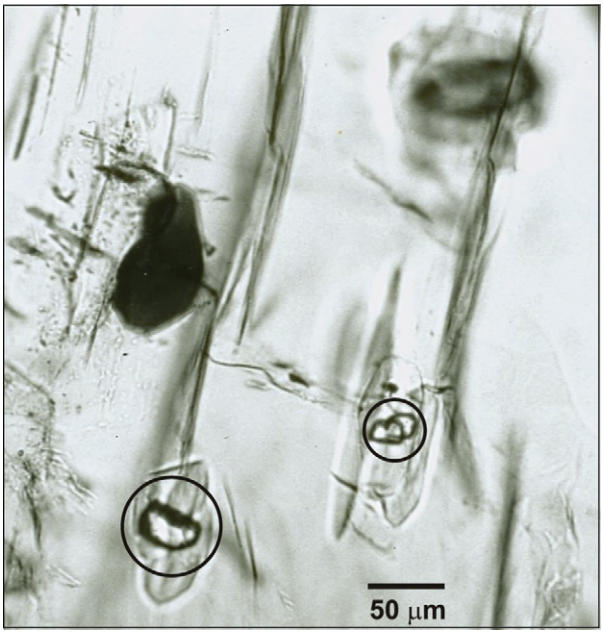

Figure 4 Zircons (black circles) in antiperthitic patches in plagioclase in enderbites from the West Uusimaa Complex in Finland (Van den Kerkhof, 1991).

2.3. Post-magmatic high-temperature metasomatism

Metasomatic features document ample evidence of percolation of an interstitial low-H_2O activity fluid phase in the form of high-salinity brines. Traces of brines are indeed found in many lower crustal rocks in the form of fluid inclusions, together with pure CO_2 fluid inclusions of variable density. The spatial distribution and density evolution of respective inclusions show that both types did occur as immiscible fluid entities during and after peak granulite metamorphic conditions (e.g., Heinrich, 2007).

High-temperature metasomatic features, i.e. myrmekites and K-feldspar microveins, are quite common in charnockites and identical to those described in granulite facies metamorphic rocks (e.g., Touret and Nijland, 2012 and references therein). The presence of these metasomatic features is an indication that a low-H_2O activity high-salinity fluid phase was present. We need to emphasise that these metasomatic features are found in both igneous and metamorphic charnockites and as such are not distinctive of either one of them.

Myrmekites (vermicular intergrowths of quartz with Ca-rich plagioclase along K-feldspar grain boundaries) are known since the beginning of microscope petrography (Michel-Lévy, 1875; Becke, 1908) and are common in igneous and high-grade metamorphic rocks (e.g., Shelley, 1993). They typically occur along the margins of large K-feldspar phenocrysts in the charnockitic augen gneisses from Hovdefjell and Ubergsmoen in southern Norway, and in the marginal-facies, garnet-bearing Ansignan charnockitic augen gneiss.

These myrmekites most likely developed during dynamic recrystallisation of the K-feldspar phenocrysts (e.g., Harlov and Wirth, 2000), followed by static recrystallisation resulting in the typical granulite microstructure (e.g., Vernon, 2004). In other words, the myrmekites form part of the granulite facies mineral assemblage and are not a late feature, which is the common interpretation for granitic rocks.

Another typical metasomatic feature associated with the presence of a high-salinity low-H_2O activity fluid is the presence of K-feldspar veining along the grain boundaries of minerals such as quartz, biotite, and plagioclase (e.g., Touret and Nijland, 2012 and references therein). Generally, K-feldspar microveins have a high albite content and are Ba enriched (Hansen et al., 1995; Franz and Harlov, 1998). It is noteworthy that in numerous occasions myrmekites are associated with K-feldspar microveins (Harlov and Wirth, 2000; Perchuk et al., 2000; Touret and Nijland, 2012) (Fig. 5). This can demonstrated with an incipient (metamorphic) charnockite from Kurunegala (Sri Lanka) (Perchuk et al., 2000) in which myrmekites and K-feldspar microveins occur along the same boundary of large mesoperthite crystals at a small distance from each other (Fig. 5a). Here, the coexistence of myrmekite and K-feldspar microveins can be explained by the following metasomatic reaction (Becke, 1908; Simpson and Wintsch, 1989): $1.25\ KAlSi_3O_8 + 0.75\ Na^+ + 0.25\ Ca^{2+} \rightarrow Na_{0.75}Ca_{0.25}Al_{1.25}Si_{2.75}O_8 + 1.25\ K^+ + SiO_2$ in which K-feldspar

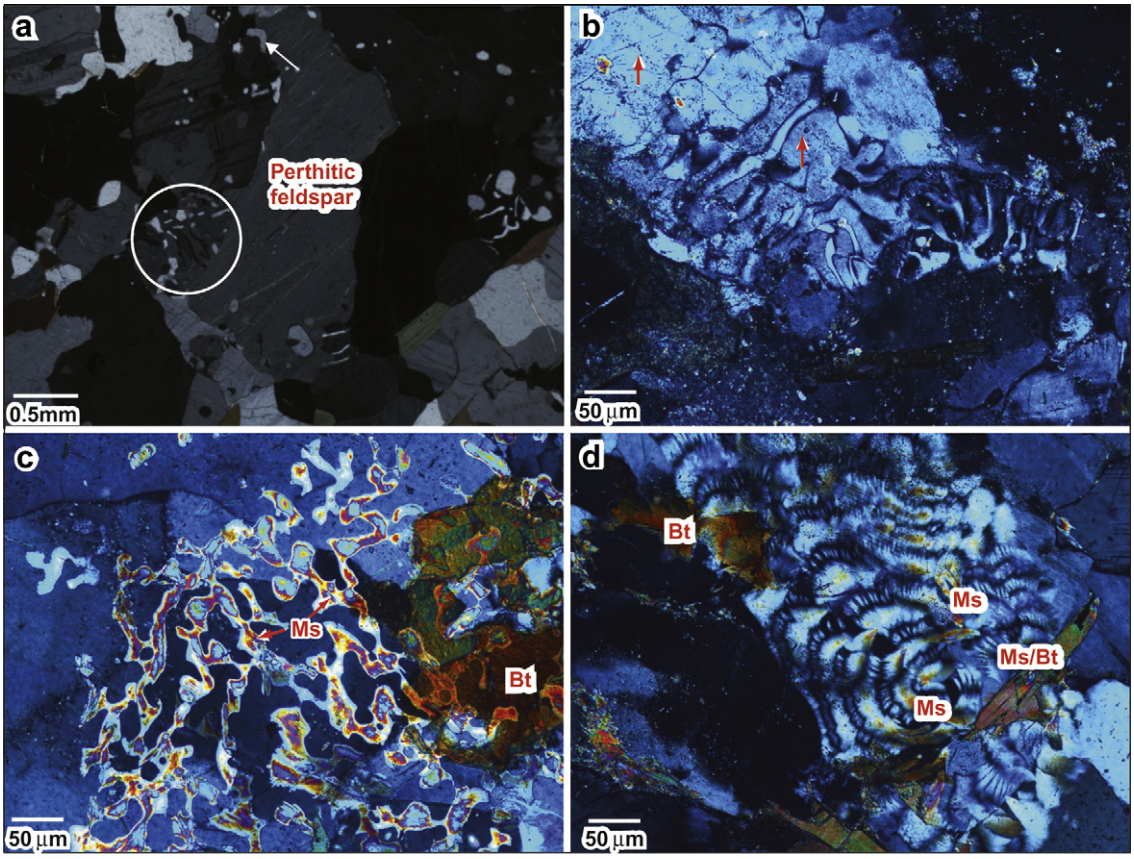

Figure 5 Microphotographs showing different examples of myrmekite and K-feldspar microveins in charnockites. a: Incipient charnockite from Kurunegala in Sri Lanka (Perchuk et al., 2000) showing myrmekite (white circle) and K-feldspar microvein (white arrows) around a single perthitic feldspar phenocryst. b: Large myrmekite with small secondary muscovite grains (bright coloured crystals in the top left corner) in garnet-bearing Ansignan charnockite from the Agly Massif (French Pyrenees). Dots (red arrows) indicate brine inclusions. c: Alteration of myrmekite to muscovite (bright coloured crystals in the centre of the microphotograph indicated by red arrows). d: Late biotite and circular array of muscovite crystals (possibly pseudomorphic after myrmekite) in garnet-bearing Ansignan charnockite.

is replaced by quartz-plagioclase intergrowths and K^+ precipitates as K-feldspar (Simpson and Wintsch, 1989) in microveins (Touret and Nijland, 2012). Supporting evidence for this interpretation comes from the presence of brine inclusions in the quartz blebs in the myrmekite (Fig. 5b), suggesting that a high-salinity fluid was present during myrmekite formation. If some fluid remains available after the formation of the microveins, K-feldspar may be replaced by muscovite (or biotite in a relatively Fe-rich environment). For example, in the Ansignan charnockite muscovite replacement occurs as a spectacular network superimposed on the mineral assemblage (Fig. 5c) or in circular aggregates, which suggest pseudomorphic replacement of the myrmekite texture (Fig. 5d).

For igneous charnockites, the metasomatic features are restricted to the charnockite body, notably in composite charnockite/granite intrusions such as the Kleivan granite in southern Norway (Konnerup-Madsen, 1977) or Varberg-Torpa charnockite intrusion in Sweden (Harlov et al., in press). This indicates that the low-H_2O activity fluids were contained in the magma and not derived from the immediate surroundings.

3. Metamorphic microstructures in charnockites

Metamorphic recrystallisation, either in charnockites emplaced at granulite conditions or in dehydrated granitic rocks, results in a typical granoblastic granulite texture (e.g., Vernon, 2004) (Fig. 6). Dynamic recrystallisation may also result in the development of elongated quartz crystals or ribbons, sometimes of extraordinary size (up to a few cm's in a finer grained matrix). This form of "platy" quartz, once considered to be a typical characteristic of (Saxony-type) granulites (Behr, 1961), is a relatively late phenomenon (Franěk et al., 2011) developed during exhumation. As mentioned previously in section 2.2.1., it is important to note that recrystallisation may result in the (partial) disappearance of solid, fluid and/or melt inclusions. Some of the solid inclusions such as zircons may be found as isolated crystals in the groundmass implying that fluid induced dissolution and re-precipitation during solid-state recrystallisation occurred. This fluid is most likely an alkali-bearing aqueous solution (Harlov and Hetherington, 2010; Harlov et al., 2011), which is likely the same as the one that is responsible for the alteration of zircon and/or monazite (through coupled dissolution and re-precipitation) found in granulites (Harlov and Dunkley, 2010; Harlov and Hetherington, 2010; Harlov et al., 2011).

The occurrence of supposed minerals of metamorphic origin, in particular garnet and also other Al-rich mineral phases such as cordierite, is sometimes used as an indication for a metamorphic origin of the charnockite. Such a hypothesis is, however, highly ambiguous: garnet could either have formed from metamorphic

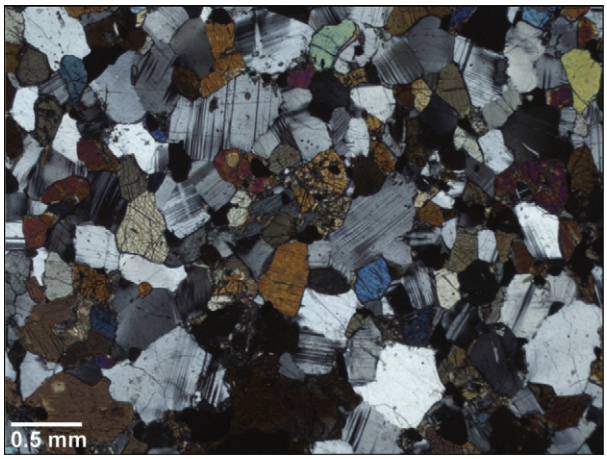

Figure 6 Recrystallised granoblastic granulite texture in norite (AMGC complex, Adirondacks).

reactions (e.g., Young et al., 1997; Frost and Frost, 2008), or from magmatic crystallisation as an alternative to pyroxene due to the relatively high Al-content of the magma (Frost and Frost, 2008). This is the case for the Ansignan igneous charnockite, which at its margins comprises garnet as a result of the assimilation of sedimentary country rocks during remelting (Respaut and Lancelot, 1983). On the other hand, the garnet in the Doddabetta charnockite in South India is most likely metamorphic in origin (Santosh and Omori, 2008). Here, the rock-forming minerals, including garnet, contain a great number of primary, high-density CO_2 inclusions (Touret and Hansteen, 1988).

A metamorphic origin for charnockite can only be inferred if textural evidence is found for the crystallisation order of orthopyroxene relative to biotite/amphibole (e.g., Percival and Mortensen, 2002). The formation of orthopyroxene according to the reactions Bt + Qtz → Opx + Kfs + H_2O and Hbl + Qtz → Opx + Cpx + Pl + Kfs + H_2O can be demonstrated with, amongst others, the general association of orthopyroxene with K-feldspar, the presence of biotite inclusion in orthopyroxene, and reaction-related intergrowths of biotite and orthopyroxene (e.g., Rajesh et al., 2011).

4. Conclusions

Petrographic study of charnockites is an essential component for the study of these rocks. Unfortunately, in too many studies only cursory attention is given to charnockite petrography. We hope that, with the availability recent publications related to the petrographic study of high-grade metamorphic and igneous rocks (e.g., Vernon, 2004; Holness et al., 2011), this will improve in the future. It must, however, realize that microstructures alone cannot always solve whether charnockites are igneous or metamorphic in origin due to high-temperature recrystallisation.

Recent advancements in the study of melt-related microstructures (Cesare et al., 2009; Holness et al., 2011) and the recent findings of melt inclusions in lower crustal rocks (Chupin et al., 1997, 2001; Bagiński et al., 2006; Cesare et al., 2009, 2011) creates new perspectives in charnockite research. So far, few studies (Chupin et al., 1997, 2001; Bagiński et al., 2006) have revealed that CO_2 (as indicated by primary fluid inclusions in magmatic feldspars in the Ansignan charnockite or in melt inclusions in zircons in the Pamir xenoliths) and brines are present at the magmatic stage in the lower crust under immiscible conditions. Further evidence for the presence of brine fluids includes the high-temperature fluid-mineral reactions at intergrain boundaries (K-feldspar microveins and myrmekites) observed in both igneous and metamorphic charnockites. It remains to be determined in each individual case whether these lower crustal fluids are the same as those present in the magmatic charnockite, or were introduced from an external source.

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